Assessing Geoheritage Values: a Case Study Using the Leschenault Peninsula and its Leeward Estuarine Lagoon, South-western Australia

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To further the disciplines of geoheritage and geoconservation, a Geoheritage "tool-kit" has been developed to systematically compile an inventory at various scales of geological and geomorphological features in a given area, assess their levels of significance, and address whether geoheritage features are treated in isolation or as inter-related suites that should be conserved as an ensemble. The Leschenault Peninsula, a retrograding Holocene dune barrier in south-western Australia, and its leeward estuarine lagoon, provide a case study of the application of this tool-kit. The barrier-and-lagoon is unique in Western Australia and comprises a wide variety of geological and geomorphological features, from large to fine scale, and varying in significance from International to State-wide to Regional. Some key features include: active parabolic dunes; an interface between dunes and estuary that is the most complex sedimentologically, hydrologically, and ecologically in Western Australia; a stratigraphy recording a complex Holocene sea level history; barrier retreat marked by parallel bands of submerged beach rock; and a sheet of calcrete above the water table. In terms of geoconservation, addressing the various features of geoheritage value in this area is best achieved by viewing the system as an integrated geopark of interactive processes, geology, and geomorphology.

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INTRODUCTION

Geoheritage and geoconservation have become significant endeavours in the conservation of important geological features. Within a broadly defined scope of geoheritage of Brocx and Semeniuk (2007), and building on Brocx (2008), a Geoheritage "tool-kit" has been developed to assess geological and geomorphological features that should be encompassed under the umbrella of geoheritage. In a given area, geoheritage features of geoconservation significance can range from large scale to fine scale, from international to local in significance, can encompass a wide range of geological/geomorphological features, and can occur in isolation, or as an inter-related suite that should be conserved as an ensemble. This Geoheritage tool kit has been designed to systematically address and assess this diversity.

This paper outlines the concepts underpinning the approach adopted for use in geoheritage and geoconservation, and describes the Geoheritage tool-kit. It provides a case study of Leschenault Peninsula and its leeward estuarine lagoon, where the tool-kit has been applied to identify sites and features therein, and evaluate their significance. This tool-kit aims to address the classification and assessment challenges for land managers and geoheritage practitioners.

SCOPE, SCALE, AND LEVELS OF SIGNIFICANCE OF GEOHERITAGE FEATURES

The term geoheritage is used as follows (after Brocx and Semeniuk 2007):

Globally, nationally, state-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, *geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference.*

This perspective definitively places many aspects of geology, previously perhaps not recognised as part of the spectrum of geoheritage, firmly under its umbrella.

While geoheritage relates to features of a geological nature, geoconservation is the action that works towards the preservation of sites of geoheritage significance once their level of significance has been determined.

Following Brocx and Semeniuk (2007), sites of geoheritage significance can be assigned to one of four conceptual categories (Figure 1): 1. as reference sites and/or type locations; 2. as sites of cultural or historical significance; 3. as geohistorical sites showing ancient sequences where the history of the earth can be determined; and 4. modern landscapes and setting where Earth processes are still active.

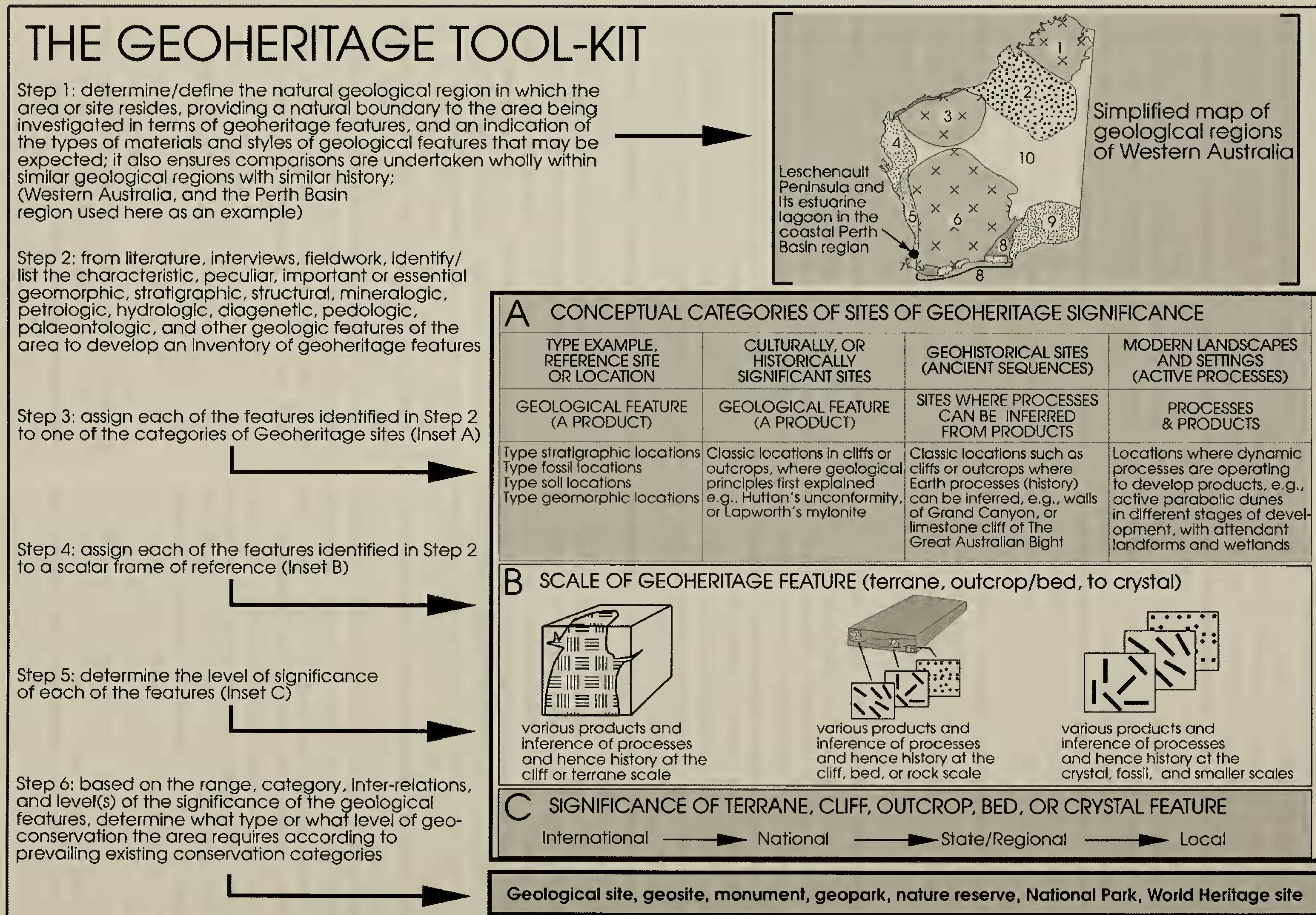
Scale is important to consider in geoheritage and geoconservation since geoheritage sites can range from landscapes and geological phenomena at montane-scale, to that of outcrops, beddings planes, or a crystal (for examples, see Brocx and Semeniuk, 2007). Formal application of scale to describe or denote geological features for assessing geoheritage and for geoconservation follows Brocx and Semeniuk (2007):

Regional scale (or megascale): geological/geomorphological features encompassed by a frame of reference of 100 km x 100 km or larger; examples include mountain range scale, or drainage basins;
Large scale (or macroscale): geological/geomorphological features encompassed by a frame of reference of 10 km x 10 km; examples large outcrop scale features, or barrier islands;
Medium scale (or mesoscale): geological/geomorphological features encompassed by a frame of reference of 1 km x 1 km or larger; examples include small mesas and their adjoining plain;
Small scale (or microscale): geological/geomorphological features encompassed by a frame of reference of 10-100 m x 10-100 m; examples include local cliff exposures;
Fine scale (or leptoscale): geological/geomorphological features encompassed by a frame of reference of 1 m x 1 m; examples include bedding scale features such as fossil beds and animal tracks;
Very fine scale: geological/geomorphological features encompassed by a frame of reference of 1 mm x 1 mm or smaller; examples include small crystals.

Levels of significance assigned to geoheritage sites have been defined for Western Australia in Brocx and Semeniuk (2007), but the principles are applicable worldwide. While various levels of significance have been used globally, nationally in Australia, and within Western Australia (viz., International, National, State-wide/Regional, and Local), there generally have not been definitions of these terms until recently (as discussed in Brocx 2008). The criteria adopted here for levels of significance are (Brocx and Semeniuk 2007):

International: one of, or a few, or the best of a given feature globally;
National: though globally relatively common, one of, or a few, or the best of a given feature Nationally;
State-wide/Regionally: though globally relatively common, and occurring throughout a Nation, one of, or a few, or the best of a given feature State-wide or Regionally;
Local: occurring commonly through the world, as well as Nationally to Regionally, but especially important to local communities.

Figure 1 OPPOSITE: The elements of the Geoheritage tool-kit showing the six steps in its application leading to assessment of types of geoconservation. The map of Western Australia in Step 1 also shows the location of the Study Area. The simplified geological regions of Western Australia are (from Brocx and Semeniuk 2010, modified from the Geological Survey of Western Australia 1990): 1. Precambrian Kimberley Region; 2. Phanerozoic Canning Basin; 3. Pilbara Region (with three Precambrian units, and a coastal fringe of Cainozoic sediments); 4. Phanerozoic Carnarvon Basin; 5. Phanerozoic Perth Basin; 6. Precambrian Yilgarn Craton; 7. Precambrian Leeuwin-Naturaliste Orogen; 8. Precambrian Fraser-Albany Orogen and Tertiary Bremer Basin; 9. Tertiary Eucla Basin; and 10. undifferentiated regions. The diagram showing the scope of geoheritage in terms of its conceptual categories (A), its scales of application (B), and potential levels of significance (C) for Steps 3-5 is adapted from Brocx (2008).


THE GEOHERITAGE TOOL-KIT
Step 1: determine/define the natural geological region in which the area or site resides, providing a natural boundary to the area being investigated in terms of geoheritage features, and an indication of the types of materials and styles of geological features that may be expected; it also ensures comparisons are undertaken wholly within similar geological regions with similar history; (Western Australia, and the Perth Basin region used here as an example)
Simplified map of geological regions of Western Australia
Leschenault Peninsula and its estuarine lagoon in the coastal Perth Basin region
1
2
3
4
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Step 2: from literature, interviews, fieldwork, identify/list the characteristic, peculiar, important or essential geomorphic, stratigraphic, structural, mineralogic, petrologic, hydrologic, diagenetic, pedologic, palaeontologic, and other geologic features of the area to develop an inventory of geoheritage features
Step 3: assign each of the features identified in Step 2 to one of the categories of Geoheritage sites (Inset A)
Step 4: assign each of the features identified in Step 2 to a scalar frame of reference (Inset B)
Step 5: determine the level of significance of each of the features (Inset C)
Step 6: based on the range, category, inter-relations, and level(s) of the significance of the geological features, determine what type or what level of geo-conservation the area requires according to prevailing existing conservation categories
A CONCEPTUAL CATEGORIES OF SITES OF GEOHERITAGE SIGNIFICANCE
TYPE EXAMPLE, REFERENCE SITE OR LOCATION
CULTURALLY, OR HISTORICALLY SIGNIFICANT SITES
GEOHISTORICAL SITES (ANCIENT SEQUENCES)
MODERN LANDSCAPES AND SETTINGS (ACTIVE PROCESSES)
GEOLOGICAL FEATURE (A PRODUCT)
GEOLOGICAL FEATURE (A PRODUCT)
SITES WHERE PROCESSES CAN BE INFERRED FROM PRODUCTS
PROCESSES & PRODUCTS
Type stratigraphic locations Type fossil locations Type soil locations Type geomorphic locations
Classic locations in cliffs or outcrops, where geological principles first explained e.g., Hutton's unconformity, or Lapworth's mylonite
Classic locations such as cliffs or outcrops where Earth processes (history) can be inferred, e.g., walls of Grand Canyon, or limestone cliff of The Great Australian Bight
Locations where dynamic processes are operating to develop products, e.g., active parabolic dunes in different stages of development, with attendant landforms and wetlands
B SCALE OF GEOHERITAGE FEATURE (terrane, outcrop/bed, to crystal)
various products and inference of processes and hence history at the cliff or terrane scale
various products and inference of processes and hence history at the cliff, bed, or rock scale
various products and inference of processes and hence history at the crystal, fossil, and smaller scales
C SIGNIFICANCE OF TERRANE, CLIFF, OUTCROP, BED, OR CRYSTAL FEATURE
International → National → State/Regional → Local
Geological site, geosite, monument, geopark, nature reserve, National Park, World Heritage site

The boxed text and illustrations labelled A, B, C, in Figure 1 summarise the scope of geoheritage in terms of its conceptual categories, its scales of application, and potential levels of significance that can be assigned to sites.

IDENTIFYING SITES OF GEOHERITAGE SIGNIFICANCE

There are a number of ways that sites of geoheritage significance may/can be identified. The British and European literature provides a history of how this has been achieved, with the final outcome being an inventory-based approach (Doyle et al 1994; Wimbledon et al. 1995, 1996; for discussion see Brocx 2008). For instance, since 1949, the assessment and subsequent selection of sites in the United Kingdom has been undertaken on the basis of a series of blocks which may be based on time, subject or regional divisions, or combinations thereof. In 2001-2002 ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy, and an alliance with the International Union of Geological Sciences and UNESCO for the purpose of compiling a European inventory for the Geosites project (ProGEO 2002).

A systematic inventory-based approach to geoheritage and geoconservation requires a procedure. Identifying geological regions and the geological essentials of those regions provides the first step to developing such a procedure in order to identify the fundamental geological features for geoheritage of a given region (Brocx and Semeniuk 2010). Clearly not all aspects of geology of the Earth are present in the one region, and clearly not all aspects of the geology of a region may be of geoheritage significance - the former, for instance, recognises the unique occurrence, rarity, or representativeness of some geological features, and the latter requires some measure of assessment of significance. The Chalk, for example, well exposed along the southern coast of England, along the Cliffs of Dover is an essential feature of geoheritage significance of the south-eastern and southern coast of England (Gallois 1965; Melville and Freshney 1982; Brocx and Semeniuk 2010). Similarly, the Grand Canyon in Arizona (Holmes 1966; Shelton 1966) is a feature of international heritage significance not found outside of its area of occurrence. In Australia, Shark Bay is a World Heritage site not replicated elsewhere globally, and some of its essential features of international significance include its large scale stratigraphy, the deep-embayed limestone coastal morphology, seagrass banks, the coquina deposits, stromatolites, high-tidal crusts, high-tidal gypsum crystals, gypsum-filled birradas, modern ooid sand banks, Pleistocene oolite, and high cliffs cut into Pleistocene limestone (Logan 1970, 1974; Brocx and Semeniuk 2010). In each of these world class examples cited above, the geoheritage essentials of a given area tend to be unique to that area.

Identifying the geological essentials of a region requires recognising those geological features that *characterise*, or are *peculiar*, to a given natural geological region. This was the approach adopted in Western Australia as part of the Regional Forests Agreement where sites of geoheritage significance were determined within a framework in which the *geological essentials* of the region were identified (Semeniuk 1998). In the Yilgarn Craton, the Precambrian rock types, features that illustrate their structural and metamorphic history, the laterite, and the landscape comprise the geological essentials of that region. On the Nullarbor Plain, the Tertiary limestone, the coastal cliffs, the karst, the cave sedimentary deposits, the late Cainozoic surficial aeolian sand sheet, and wetlands would be identified.

The geological essentials of a region can be identified using a staged three-pronged approach to compile an information database on the geology of an area and at the same time potentially identifying sites of geoheritage significance. The first draws on the experience of geologists as published in the literature. The second seeks the views of geologists still practising in the field (through questionnaires/ interviews); this approach provides information and personal insights about the geoheritage potential of an area. The third, after identifying gaps in information seeks to systematically obtain further information based on regional geology. For all three approaches, there will be some degree of overlap in information and outcomes.

Identifying the various geological regions, and their contained/intrinsic features, therefore, is the first stage of a systematic inventory-based approach to developing a database for sites of geoheritage significance. This does not necessarily translate to just listing isolated sites of geoheritage significance but also attempts to identify ensembles of features where they are inter-related. The next stage would be to locate good examples, regardless of scale, of these features or of inter-related ensembles of features, and assess them according to the significance criteria outlined above.

THE GEOHERITAGE TOOL-KIT: A SYSTEMATIC PROCEDURE TO IDENTIFY AND ASSESS SITES OF GEOHERITAGE SIGNIFICANCE

The Geoheritage tool-kit provides the procedure to identify geological components across various geological sub-disciplines and at various scales, to assign geological sites to various conceptual categories of geoheritage, and to assess the levels of significance of the various geological features (Figure 1). The procedures outlined in Steps 1-6 below assume that the wider definition of what constitutes 'geoheritage', as discussed in Brocx and Semeniuk (2007), is being applied.

Step 6 of the procedure, after an assessment of the range, categories, inter-relationships, and level of significance of the geological features, determines what type and what level of geoconservation the area requires – Regional/State, National, or International.

Once the inventory of components and their level of significance are compiled, and enough geological features have ranked as being of significance, or a few rank as being of high significance, Step 6 is used to determine whether the area can be proposed/proffered for geoconservation at a Regional, State, National or International level for one or a few of its components, or for the integrated ensemble of its components. If the latter, the area may qualify to be viewed as a geological park or a geopark (see Discussion later). The area may be proposed/proffered for geoconservation especially if there is a range of inter-related geological features that all ranked highly in assessment of significance.

THE LESCHENAULT PENINSULA AND ITS LEEWARD ESTUARINE LAGOON - A DESCRIPTION

The Leschenault Peninsula and its leeward estuarine lagoon (the Leschenault Inlet estuary) located in south-western Australia (Figure 1), provide an excellent case study of how the Geoheritage tool-kit can be applied, as there is a wide range of geological features that range in scale from large scale to fine scale, cross a wide range of geological phenomena, and range in significance from International, National to State-wide. Selected key features of the stratigraphy, geomorphology, sea level history, diagenesis, and pedology of this area are presented in Figure 2.

The Leschenault Peninsula is the only Holocene linear dune barrier system in Western Australia. Its leeward estuarine lagoon is one of four large estuaries located along the south-western coast of Western Australia (see Semeniuk et al. 2000a, 2010 for comparative detail) developed along the shore of the Swan Coastal Plain, the surface expression of the Perth Basin.

In terms of classification for comparative coastal geoheritage purposes, Brocx and Semeniuk (2010) assign the Leschenault Peninsula and its lagoon to the Perth Basin Geological Region, and assign it to Coastal Type 7 and Coastal Type 11, i.e., a coast constructed by sedimentation with superimposed erosion, and a depositional coast recording Holocene history, respectively.

The text below describing the Leschenault Peninsula and its leeward estuarine lagoon, in terms of its geology, geomorphology and active processes, draws only on the essential patterns of this barrier and estuarine system from the published literature.

The dune barrier is located in a subhumid climate with mean annual rainfall of 880 mm, an annual evaporation of 1300 mm (Bureau of Meteorology 1988), an onshore (sea breeze) and offshore (land breeze) wind system, with winds reaching 15 m/s during summer and mean speeds up to 20 m/s during winter storms (Semeniuk and Meagher 1981a). The barrier coast faces the open Indian Ocean, with swell and wind waves directly impinging on the shore without offshore barriers perturbating, dissipating, or dampening the wave fields; tides are microtidal (Searle and Semeniuk 1985). For winter storms that derive from northwest, the estuarine lagoon has a long fetch to generate storm waves along the length of the estuarine lagoon.

The Leschenault Peninsula is a linear retrograding dune barrier, and is the southern part of the Leschenault-Preston Barrier (Semeniuk 1996) that formed during the post-glacial transgression when sea level reached near its present position in the Holocene ~ 7000 years ago (Semeniuk et al. 2000a). The initial, longer, more extensive, early Holocene barrier (75 km long, and approximately 0.5-1.5 km wide) formed because, unlike the rest of coastal south-western Australia, which is dominated by lines of offshore limestone islands, submerged ridges and reefs, associated onshore cuspate forelands and other sandy accumulations (formed leeward of the discontinuous and perforated offshore aeolian limestone barrier), and limestone rocky shores (Searle and Semeniuk 1985), the coast between Preston and Leschenault Peninsula offshore is shelter-free (i.e. without offshore limestone islands, ridges, and reefs), and subject directly to swell and wind waves (Searle and Semeniuk 1985). As such, instead of discrete

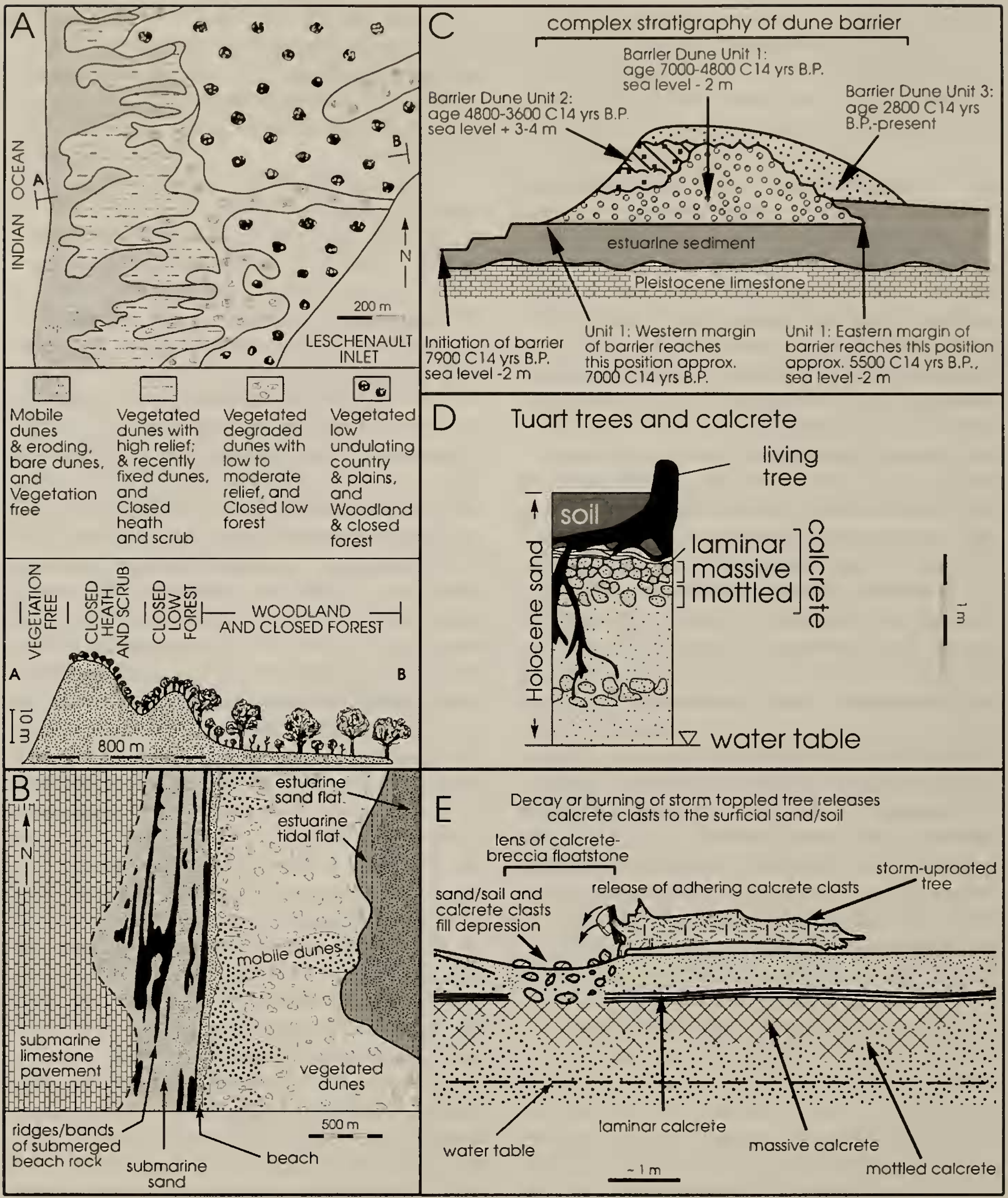


Figure 2: Selected examples of key geological and geomorphological features of geoheritage significance in the Leschenault Peninsula area. A. Map showing geomorphic and vegetation units of the Peninsula and cross section showing the change from west to east from relatively high relief terrain to undulating plains (Semeniuk & Meagher 1981a). B. Map showing ridges and bands of submerged beach rock seaward of the Leschenault Peninsula (Semeniuk & Meagher 1981a). C. The complex stratigraphy of the barrier showing its internal units and their ages relative to MSL (Semeniuk 1985). D. Calcrete forming above the water table by tuart trees (Semeniuk & Meagher 1981b). E. Development of lenses of calcrete breccia floatstone in soils following decay and/or burning of storm-uprooted trees that have ripped up calcrete during their upheaval (Semeniuk 1986b).

cuspate forelands and limestone rocky shores, that typify the rest of south-western Australia's shores, the coast has developed this extensive linear barrier.

The Leschenault Peninsula dune barrier, 15 km long, 15-30 m high, at the southern end of the Leschenault-Preston Barrier, is narrow, generally 0.5-1.0 km wide, and composed of overlapping eastward migrating parabolic dunes in various stages of mobility and fixation (Figures 2A, 2B, 2C and 3B). The gradation in time in landscape-and-vegetation evolution of these dunes are: mobile parabolic dunes, grading to fixed parabolic dunes with heath cover and incipient to weakly developed humic soils, to (naturally) geomorphically degraded parabolic dunes with forest cover and strongly developed but thin humic soils, to (naturally) geomorphically degraded undulating plains and plains with a woodland cover of tuart trees (*Eucalyptus gomphocephala*) and strongly developed thick humic soils (Figure 2A; Semeniuk and Meagher 1981a). The stratigraphy of the barrier is complex (Figure 2C), reflecting a complex Holocene sea level history and barrier development with a sea level –2 m AHD between 7000 and 3500 years BP, a sea level +3-4 m AHD some 3500-2000 years BP, and with a sea level falling to present level from 2000 years BP to the present (Semeniuk 1985), the result of local tectonism (Semeniuk and Searle 1986). A sheet of calcrete is forming in the zone of capillary rise above the modern water table (Figure 2D), induced by plant extraction of groundwater, leaving a residue of fine grained calcite (around the tuart tree root hairs) that accumulates and coalesces to form mottles, and then (coalescing of mottles to form) massive calcrete, capped by laminar calcrete (Semeniuk and Meagher 1981b). Wind excavation of sand in the bowls of the parabolic dunes exposes the calcrete sheet, which forms a floor to the parabolic dune bowl. Plains with tuart woodlands develop sheets of calcrete, while copses of isolated tuart stands develop lenses of calcrete. While this copse *versus* woodland/forest association is present on the Leschenault Peninsula, it is also reflective of a climate gradient: forests and woodlands of tuarts predominate in humid climates and develop sheets of calcrete in the zone of capillary rise, while copses and isolated stands of tuarts in less humid climates develop lenses of calcrete in the zone of capillary rise (Semeniuk 1986a).

Since the level of the water table under Leschenault Peninsula is and has been related to the position of MSL, then calcrete formed earlier in the Holocene under different levels of MSL and different heights of the water table is at lower or higher stratigraphic levels than the modern calcrete sheet. Further, calcrete occurs as lenses at these different stratigraphic levels, indicating that the tuarts earlier in the Holocene formed copse vegetation formations and not woodlands and forests, thus signalling a different climate. These higher or lower stratigraphic level calcrete lenses have been used to reconstruct Holocene climate (Semeniuk and Searle 1985; Semeniuk 1986a).

Periodically, major storms and cyclones impact on the dune barrier, up-rooting the large trees and in the process locally ripping up the calcrete sheet within which their roots are embedded, creating a depression in the soil sheet. Later filling of the depression by sheet wash and fragments of calcrete develops a lens of calcrete breccia floatstone (Semeniuk 1986b). This process, on-going during the later Holocene, has developed isolated lenses of the calcrete breccia floatstone within the soils underlying the woodland plains (Figure 2E).

In the core of the dune barrier there is a "shoestring" or prism of freshwater bordered to the sea and to the estuary by saline water, with an inclined saline water / freshwater interface on both sides. Freshwater discharges by seepage to the sea shore resulting in the formation of beach rock (Semeniuk and Searle 1985), and to the estuary shore resulting in ecological responses (Cresswell 2000; Pen et al. 2000; Semeniuk et al. 2000b), calcitisation of estuarine plant roots by encrustation and permineralisation, and precipitation of calcitic laminae (Semeniuk 2010).

Beach rock, formed at the shoreline of the seaward edge of the barrier with time-staggered coastal retreat during periodic storms and cyclones, is left stranded as a submerged ridge or band of cemented sand (rock) off shore from the barrier (Figure 2B). Successive periods of formation of beach rock, and retreat of the barrier during storms, has left a series of shore-parallel bands and ridges of this rock reflecting the various former position of the shoreline of the retreating dune barrier (Semeniuk and Searle 1987).

The Leschenault Inlet estuary, leeward of the dune barrier, is an elongate shore-parallel, shallow water estuarine lagoon with distinctive patterns of bathymetry and geomorphology, framed to the east by the Mandurah-Eaton Ridge (a Pleistocene quartz sand ridge; Semeniuk 1997), to the west by the Holocene dune barrier, and to the south by two deltas Semeniuk 2000; Semeniuk et al. 2000a). One delta is tide-dominated (the Preston River Delta); the other overall is fluvial-dominated but asymmetric, with the southern part fluvial-dominated, and the northern partly storm-developed (the Collie River Delta). The estuarine lagoon is diurnally microtidal, wave-dominated and wind-current-driven. Estuarine waters are annually poikilosaline, alternating between brackish/marine salinity in winter and marine salinity in summer (Wurm and Semeniuk 2000). At the large scale, stratigraphic relationships within the system are relatively simple (Semeniuk 2000). Estuarine sediments to the east onlap the Pleistocene quartz sand ridge, and Holocene dune barrier sands encroach over estuarine sediments to the west. Sedimentary patterns are underpinned by geomorphology and bathymetry, and linked to the lithologic nature of the dune terrain bordering the lagoon, as well as the nature of shorelines and the reworking of sources and hydrodynamics; with muddy sediments accumulating in deeper water basins and semi-sheltered environments, and sand accumulating on exposed platforms, dune margins, or in deltas (Pen et al. 2000). There are facies changes in the estuary from east to west, dependent on the source of shore sand, the bathymetry, and facies changes from south to north, from delta-dominated in the south to shallow mud flat dominated in the north (where south-westerly winds have carried mud in suspension to north to form in a large accumulation) (Semeniuk 2000). Small scale geomorphology and stratigraphic relationships along the dune barrier margin with the estuary are more complex, with spits, cheniers, pockets of mud in dune finger corridors, aprons of sand around the parabolic dunes that have encroached into the estuary, and interfingering of the dune sand with estuarine sediment (Semeniuk 2000). As noted above, freshwater discharges from the barrier into the estuary form shore seepages, which are important for shore vegetation and fauna (Cresswell 2000). In one case, the freshwater seepage sustains a stand of mangroves, *Avicennia marina* (Semeniuk et al. 2000b).

Leschenault Inlet estuary is unique in south-western Australia for several reasons. Formed behind a shore-parallel dune barrier, and wholly Holocene in age, its estuarine geomorphology and hydrologic structure are different to other local estuaries such as the Swan River Estuary and the Peel-Harvey Estuary (Semeniuk et al. 2000a). The estuary does not represent a classic and simple river-to-sea transition, but has rivers entering at the southern end of the long north-south oriented lagoon that had formed by marine processes rather than fluvial erosion. Leschenault Inlet estuary has also had a complicated Holocene sea level history, resulting in complexity of its shores. Its western shore is further complicated as parabolic dunes encroach into the estuary, producing a varied assemblage of shore types and stratigraphic/hydrologic situations. The complex of shores and wetland types peripheral to the estuary support a variety of fringing vegetation assemblages as linked to shoreline geomorphology, stratigraphy, hydrology and hydrochemistry (Pen et al. 2000). Consequently, Leschenault Inlet estuary is a classic area for studies of how geodiversity underpins both local alpha biodiversity and beta biodiversity (cf. Whittaker 1972) and the ecology of estuarine peripheral vegetation. In this context, the system ranks as one of the most significant in southern and south-western Australia (Table 4 in Pen et al 2000). Through its proximity to the Leeuwin Current, the estuary also supports the most southern occurrence in Western Australia of the mangrove *Avicennia marina*, and the array of landforms and vegetation in and around the estuary as related to bathymetry, geomorphic setting and habitats, combine to create an important class room for Holocene estuarine shore palynology (Semeniuk et al. 2000c).

Revets (2000) documented a rich (neo) palaeontological assemblage of Holocene foraminifera in the Leschenault Inlet estuary with a Fisher alpha index of 30.47 for the whole estuary. At one location opposite the Collie River delta, on a shallow water muddy sand platform, Revets (2000) found the richest biodiversity of (neo)palaeontological foraminiferal assemblage globally, with a Fisher alpha index of 31.87 – essentially the most species-rich assemblage of foraminifera in any estuary in the world.

THE GEOHERITAGE ESSENTIALS OF THE LESCHENAULT PENINSULA AND ITS ESTUARINE LAGOON

For the Leschenault Peninsula area and its associated estuarine lagoon, there are many features that comprise its geoheritage essentials. Whereas there are linear barriers and linear lagoons elsewhere in Australia (e.g., the Younghusband Peninsula and its lagoon, on The Coorong; (von der Borsch and Lock 1979; Geddes and Butler 1984; Murray-Wallace et al. 1999) this linear retrograding dune barrier sheltering a linear estuarine lagoon is unique in Western Australia. It is wholly Holocene in age. By contrast, the coastal barriers of the Coorong to Mount Gambier Coastal Plain (e.g., the Younghusband Peninsula), though Holocene linear barriers, appear to have a core of Pleistocene limestone (Belperio 1995; Murray-Wallace et al. 1999). Additionally, because of the history of relative MSL, tuart-developed calcrete, and mobile parabolic dunes interfacing with the estuary, the Leschenault Peninsula and its associated lagoon has developed a range of geomorphic, stratigraphic, hydrological, hydrochemical, and digenetic features distinctive and Internationally and/or Nationally unique to this system.

Table 1. Essential features of geoheritage that characterise the Leschenault Peninsula and its associated estuarine lagoon, ordered from dune to estuary

1.	linear retrograding Holocene dune barrier in south-western Australia
2.	active parabolic dunes within the barrier
3.	gradational range of landscapes from active mobile dune to undulating plain
4.	calcrete forming in the modern zone of capillary rise
5.	lenses of calcrete at high stratigraphic levels
6.	calcrete exposed in deflation bowls of parabolic dunes
7.	calcrete breccia floatstone
8.	beach rock forming in the tidal zone
9.	stranded beach rock forming submerged shore-parallel bands and ridges
10.	complex stratigraphy of the dune barrier
11.	Holocene sea level history recorded in the stratigraphy
12.	complex of shorelines and stratigraphy along the dune/estuary interface
13.	freshwater seepage along the dune/estuary interface and complex ecology
14.	a prominent mangrove stand developed along the dune/estuary interface
15.	estuary shore landforms along the western estuary shore, graded south to north
16.	calcite encrustation of sea rush roots in the tidal zone
17.	rich biodiversity of Holocene estuarine foraminifera
18.	well-documented Holocene palynological record as a model for estuaries
19.	north-south and east-west patterns in sediments and stratigraphy of the estuary
20.	an intra-estuarine delta
21.	peripheral wetlands along western and eastern estuary margin
22.	stratigraphic type sections

The Leschenault Peninsula and its leeward estuarine lagoon also have several type locations for Holocene stratigraphic units, viz., members within the Safety Bay Sand (the Burrangenup Member, the Rosamel Member, the Vittoria Member, the Koombana Beach Rock, the Binningup Calcrete), and the estuarine Leschenault Formation (Semeniuk 1983).

The key features of geology and geomorphology, at various scales, that are identified, and that are important and distinctive to the region, are listed in Table 1. The large scale features of the Leschenault Peninsula area and its associated estuarine lagoon are listed only to identify the important geological framework for this region. It is also axiomatic that if features at smaller scales *within* the Leschenault Peninsula area and its associated estuarine lagoon rank as significant at the National or State-wide level, then the system that contains them also should be ranked as significant at the National or State-wide level.

The grading of the essential geoheritage features in the Leschenault Peninsula and the Leschenault Inlet estuary with respect to International, National and State-wide/Regional significance, and the rationale for that assessment are outlined in Table 2. Application of the Geoheritage tool-kit to the Leschenault Peninsula and its leeward estuarine lagoon is illustrated in Figure 3: the categories of sites of geoheritage significance are identified, key selected features at the various scales are provided as examples, and the essential features are graded as to their level of significance.

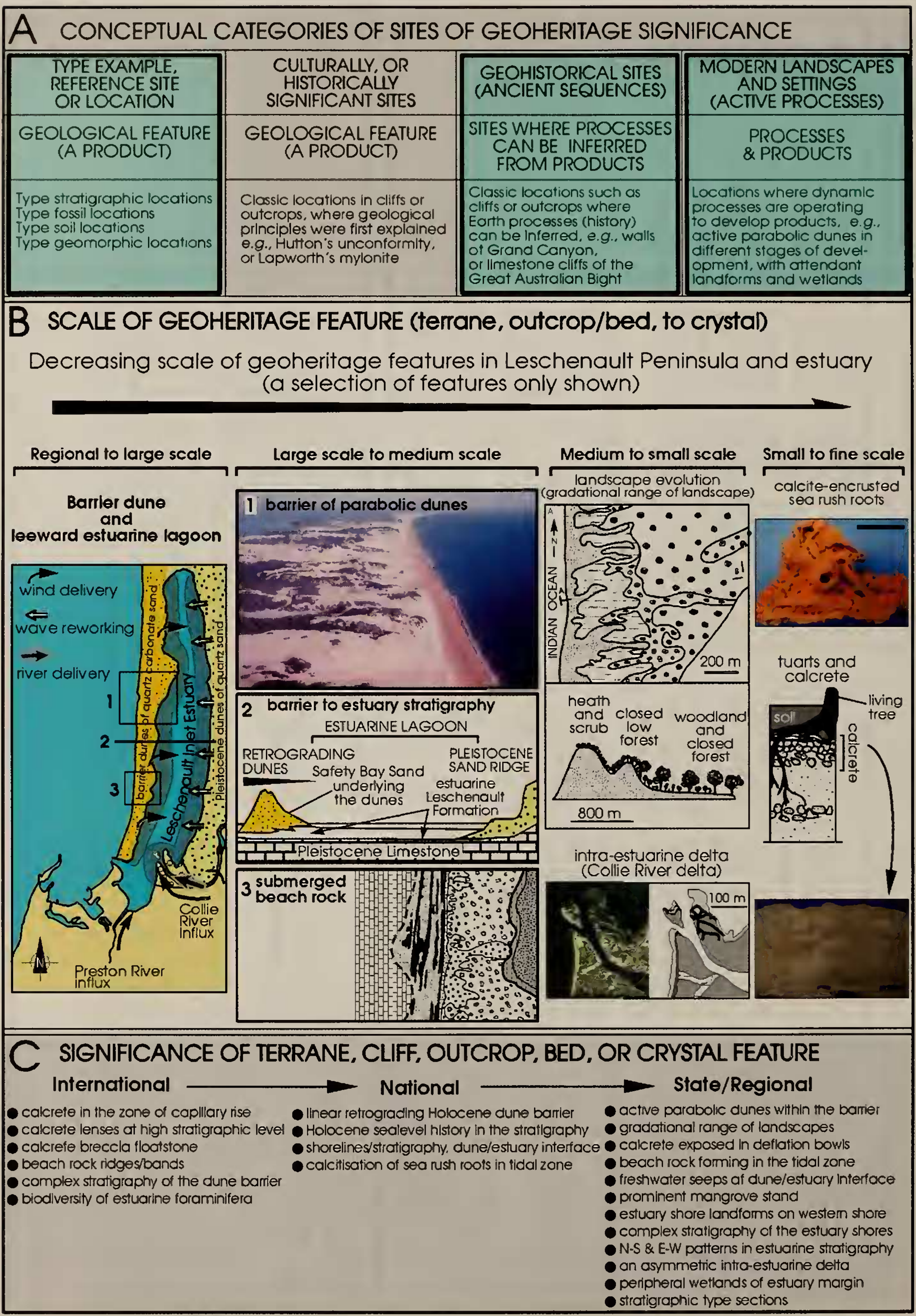
SUMMARY AND DISCUSSION

This paper has endeavoured to provide a description of the "state of the art" of geoheritage and geoconservation in Western Australia, and a case study of the application of the techniques of identification of features and assessment of features, i.e., the Geoheritage tool-kit. The main objectives of earlier work of Brocx and Semeniuk (2007) and Brocx (2008) were to define geoheritage within a broader context of geology, conceptualise the various categories of what constitutes geoheritage, deal with the issue of scale, and more rigorously define levels of significance. These outcomes are essential foundations to designing classification and assessment systems to

Table 2. Grading of essential features of geoheritage significance in Leschenault Peninsula and its Leschenault Inlet estuary, and the rationale for the assessment.

Geological feature and its scale	Type of site (category of site from Figure 2)	Significance	Rationale for assigning the level of significance
calcrete in zone of capillary rise; small to fine scale feature	modern landscapes and setting (active processes)	International	first and only description to date globally of Holocene calcrete forming in the zone of capillary rise in relationship to plants
calcrete at high/low stratigraphic levels; small to fine scale feature	geohistorical site	International	first use of Holocene calcrete to reconstruct Holocene climate history
calcrete breccia floatstone	modern landscapes and setting (active processes)	International	first description of lenses of Holocene calcrete breccia floatstone in soils, developed as a consequence of tree heave by storms
complex stratigraphy of barrier; medium scale feature	geohistorical site	International	one of the most complex dune barriers stratigraphically in the world because of the local sea level history superimposed on dune barrier development
stranded submerged beach rock forming bands/ridges; medium to small scale feature	modern landscapes and setting (active processes), and geohistorical site	International	first and only description to date globally of stranded beach rock forming submerged shore-parallel bands/ridges with barrier retreat
biodiversity of foraminifera; very fine scale feature	modern landscapes and setting	International	richest biodiversity of Holocene estuarine foraminifera (neo)palaeontologically in the world
linear retrograding barrier; large to medium scale feature	modern landscapes and setting (active processes)	National	the only linear retrograding Holocene dune barrier barring a barrier-parallel linear lagoon in Western Australia, and only one of a few nationally
Holocene sea level history recorded in the stratigraphy; small scale feature	geohistorical site	National	unique Holocene sea level history recorded in the stratigraphy and reflecting local tectonism
complex shorelines/stratigraphy along the dune/estuary interface; large to medium scale feature	modern landscapes and setting (active processes)	National	since the dune barrier is only one of a few occurring Nationally, the complex of shorelines and stratigraphy at the dune/estuary interface in this climate setting are Nationally uncommon
calcite encrustation of sea rush roots; fine to very fine scale feature	modern landscapes and setting (active processes)	National	encrustation (and permineralisation) by calcite, Mg-calcite, and dolomite of sea rush roots in the tidal zone at the dune/estuary interface in this climate setting is Nationally uncommon
well-documented Holocene palynological record as a model for estuaries; very fine scale feature	modern landscapes and setting (active processes)	National	the documented patterns of pollen distribution in the Holocene estuarine sequence provides model to interpret estuarine palynology

active parabolic dunes in barrier; medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	the geometry and style of active parabolic dune development within the barrier is unique in the State; compared with other parabolic dunes that change shape and orientation with respect to progressively changing wind directions and wind speed latitudinally (see Semeniuk et al. 1989)
gradational range of landscapes: mobile dune to undulating plain; large to medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	in this climate, with the vegetation contributing organic matter to soils, and the natural geomorphic gradation from mobile dunes to fixed dunes to plains, this transition is unique in Western Australia
calcrete exposed in deflation bowls of parabolic dunes; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	normally, dune bowl excavation proceeds to the water table and forms dune slacks, but calcrete arrests this excavation; calcrete exposed in bowls is a unique landscape feature in this calcrete-and-parabolic dune setting in Western Australia
beach rock in the tidal zone	modern landscapes and setting (active processes)	State-wide/ Regional	this type of beach rock is restricted to this part of Western Australia, and reflects the hydrochemical interchange between the freshwater reservoir in the barrier and the marine shore
freshwater seepage at dune/estuary interface; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	freshwater seepage along the dune/ estuary interface produces complex ecological responses, and results in the second most complex estuarine shore in Western Australia
mangrove stand at dune/estuary interface; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	a prominent mangrove stand is formed at the dune/estuary interface where there is freshwater seepage from the tip of a parabolic dune encroaching into estuary
estuary western shore landforms graded south to north; large scale feature	modern landscapes and setting	State-wide/ Regional	the south to north transition of shore landforms along the western estuary shore reflects the unique nature of the northerly oriented linear lagoon, and its relation to wind and wave dynamics, and is a feature of State significance
north-south and east-west patterns in sediments and stratigraphy of estuary; large to medium scale feature	modern landscapes and setting	State-wide/ Regional	the linear lagoon bordered by distinct landforms and provenances has resulted north-south and east-west patterns in sediments and stratigraphy of the estuary that are unique in Western Australia
an intra-estuarine delta; medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	at the southern end of a north-south oriented estuarine lagoon, the Collie Delta is asymmetric reflecting fluvial construction and a storm influenced northern part that faces the long fetch of the lagoon - a feature unique in Western Australia
peripheral wetlands along western and eastern shore of estuary; large scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	the stratigraphy, landforms, and freshwater seepage along the estuarine shores from the dune barrier and the Eaton Ridge has resulted in distinct peripheral wetlands along western and eastern shores of the estuary that are found nowhere else in Western Australia
stratigraphic type sections; small scale feature	reference sites	State-wide/ Regional	the area contains a number of stratigraphic type sections



A CONCEPTUAL CATEGORIES OF SITES OF GEOHERITAGE SIGNIFICANCE
TYPE EXAMPLE, REFERENCE SITE OR LOCATION
CULTURALLY, OR HISTORICALLY SIGNIFICANT SITES
GEOHISTORICAL SITES (ANCIENT SEQUENCES)
MODERN LANDSCAPES AND SETTINGS (ACTIVE PROCESSES)
GEOLOGICAL FEATURE (A PRODUCT)
GEOLOGICAL FEATURE (A PRODUCT)
SITES WHERE PROCESSES CAN BE INFERRED FROM PRODUCTS
PROCESSES & PRODUCTS
Type stratigraphic locations
Type fossil locations
Type soil locations
Type geomorphic locations
Classic locations in cliffs or outcrops, where geological principles were first explained e.g., Hutton's unconformity, or Lapworth's mylonite
Classic locations such as cliffs or outcrops where Earth processes (history) can be inferred, e.g., walls of Grand Canyon, or limestone cliffs of the Great Australian Bight
Locations where dynamic processes are operating to develop products, e.g., active parabolic dunes in different stages of development, with attendant landforms and wetlands
B SCALE OF GEOHERITAGE FEATURE (terrane, outcrop/bed, to crystal)
Decreasing scale of geoheritage features in Leschenault Peninsula and estuary (a selection of features only shown)
Regional to large scale
Large scale to medium scale
Medium to small scale
Small to fine scale
Barrier dune and leeward estuarine lagoon
wind delivery
wave reworking
river delivery
1
2
3
barrier dunes of quartz carbonate sand
Leschenault Inlet Estuary
Pleistocene dunes of quartz sand
Collie River influx
Preston River influx
N
1 barrier of parabolic dunes
2 barrier to estuary stratigraphy
ESTUARINE LAGOON
RETROGRADING DUNES
Safety Bay Sand underlying the dunes
PLEISTOCENE SAND RIDGE
estuarine Leschenault Formation
Pleistocene Limestone
3 submerged beach rock
landscape evolution (gradational range of landscape)
INDIAN OCEAN
N
200 m
heath and scrub
closed low forest
woodland and closed forest
800 m
intra-estuarine delta (Collie River delta)
100 m
calcite-encrusted sea rush roots
tuarts and calcrete
living tree
soil
calcrete
C SIGNIFICANCE OF TERRANE, CLIFF, OUTCROP, BED, OR CRYSTAL FEATURE
International
National
State/Regional
● calcrete in the zone of capillary rise
● calcrete lenses at high stratigraphic level
● calcrete breccia floatstone
● beach rock ridges/bands
● complex stratigraphy of the dune barrier
● biodiversity of estuarine foraminifera
● linear retrograding Holocene dune barrier
● Holocene sealevel history in the stratigraphy
● shorelines/stratigraphy, dune/estuary interface
● calcitisation of sea rush roots in tidal zone
● active parabolic dunes within the barrier
● gradational range of landscapes
● calcrete exposed in deflation bowls
● beach rock forming in the tidal zone
● freshwater seeps at dune/estuary interface
● prominent mangrove stand
● estuary shore landforms on western shore
● complex stratigraphy of the estuary shores
● N-S & E-W patterns in estuarine stratigraphy
● an asymmetric intra-estuarine delta
● peripheral wetlands of estuary margin
● stratigraphic type sections

identify sites of geoheritage significance in Western Australia, and elsewhere.

In this case study along the south-western coast of Western Australia, the Geoheritage tool-kit has been applied to identify sites of geoheritage significance, deriving from an inventory-based approach that rigorously assigns a level of significance to geological features regardless of their scale and within a framework of the broadest possible definition of geoscience. While the Leschenault Peninsula and leeward estuarine lagoon was used as a case study because it contains a wide variety of geological and geomorphological features ranging from large scale to fine and very fine scale, and varying in significance from International to State-wide, in fact the Geoheritage tool-kit can applied to any geological site, or region, to determine geoheritage values for conservation and management.

The Geoheritage tool-kit provides a method to give context to a range of inter-related features such as those found in the Leschenault Peninsula and leeward estuarine lagoon because there is a need not only for geoconservation of large scale features but also of significant smaller scale features in this system, and geoconservation of individual features as well as integrated geoconservation system conserving the suite as an inter-related ensemble. Thus in terms of geoconservation, addressing the various features of geoheritage value in the Leschenault Peninsula area and its associated estuarine lagoon, that individually rank from Regionally significant to Nationally to Internationally significant, is best achieved by viewing the system holistically as an integrated (geo)park of interactive processes, geology, and geomorphology. Therefore, given this background and the important and unique nature of the Leschenault Peninsula area, it should be viewed as a National or State geopark, within which there are also features of International significance, thus integrating the many smaller-scale features of geology and geomorphology into a single geoconservation unit. In the UNESCO definition of a geopark, the Leschenault Peninsula and its associated estuarine lagoon qualifies in containing numerous "*geological heritage sites of special scientific importance*". The various components of the geoheritage of the area should be viewed not in isolation, as type locations, or "best example of a given feature", but as the integrated system of geological products and as integrated systems of processes-and-products. Landscape evolution is an example of these principles. Calcrete, intra-estuarine deltas, and their asymmetric nature, the wetlands, the dunes of the barrier dunes, and the distinctive and complex estuarine shore stratigraphy also provide examples. Fine and very fine scale features, such as calcitisation of sea rush roots by encrustation and permineralisation under the high tidal flat, that is dependent on the groundwater seepage from the adjoining dunes, provide another specific example of these principles, in that without the calcite-bearing dune sand, the parabolic dune encroaching into the estuary, and the nature of the dune sand to estuary hydrology, there would not be the calcitisation of the sea rush roots.

While the Leschenault Peninsula and its estuarine lagoon are unique in Western Australia, and has been afforded National significance in that it is 'one or a few of such systems occurring Nationally' (Department of Conservation and Land Management 1998), in fact, it may be unique in Australia. Firstly, though linear barriers are common along the eastern seaboard of Australia, they generally bar digitate embayments and estuaries formed by postglacial marine flooding of riverine drainage patterns such that the lagoons are digitate to circular (Roy and Crawford 1979; Roy 1984; Roy et al. 1994), and as such as not

Figure 3 OPPOSITE: Application of the Geoheritage tool-kit to the Leschenault Peninsula and its leeward estuarine lagoon. In inset A, the categories of geoheritage applicable to this area are highlighted in blue. In inset B, some selected features of geoheritage significance are illustrated, graded in decreasing scale from left to right. Under the column "regional to large scale", the map of the barrier and lagoon shows a boxed inset 1, a transect labelled 2, and a boxed inset 3 – these are shown in detail as (1), (2), and (3) under the column of "large to medium scale". Under "large to medium scale", there is (1) an oblique aerial view of the barrier showing mobile and vegetated dunes, (2) a cross-section of barrier-to-lagoon stratigraphic relationships, and (3) the map of submerged beach rock (whose legend is in Figure 2). Under "medium to small scale" there is map of the landscape setting and associated vegetation, and their cross-section, and a map of the asymmetric Collie River delta. Under "small to fine scale" there is a photograph of the calcitised sea rush roots (from Semeniuk 2010), a diagram of the relationship of calcrete to tuart trees and the water table, and a photograph of a polished vertical slab of the calcrete (details of the calcrete profile are in Figure 2). The bar scale for the calcitised sea rush roots and the calcrete in the column of "small to fine scale" is 2 cm. In inset C. all features listed in Table 1 are allocated to a level of significance to comparatively illustrate the range of features and their significance.

comparable. Linear barriers protecting linear lagoons are not so common. Secondly, the nearest analogue to the Leschenault barrier-and-lagoon system is the Younghusband Peninsula barring The Coorong, however, it appears that ensemble of barriers in the Coorong Coastal Plain region may be founded on a low relief Pleistocene limestone ridge as an earlier barrier of the last interglacial period (Belperio 1995; Harvey 2006). Thirdly, focusing on the lagoons themselves, the geomorphology and sedimentary fill of the estuarine lagoon of Leschenault Inlet estuary and The Coorong are wholly dissimilar, the former comprised of provenance-specific sand platforms and deeper water terrigenous mud, with the sediments still filling the linear depression (Semeniuk 2000), and the latter essentially a carbonate-dominated sedimentary accumulation that has filled the linear depression (Alderman and Skinner 1957; von der Borch and Lock 1979; Harvey 2006).

Calcrete also is significant in the Leschenault Peninsula dune barrier. While calcrete has been recorded from another calcareous barriers (e.g., the Younghusband Peninsula; Warren 1983), these latter types are pedogenic and not related to the water table and tree-induced precipitation. Indeed, the tree responsible for calcrete precipitation is biogeographically unique to south-western Australia, and hence this type of calcrete is restricted to the south-western Australian region. A consequence of the calcrete sheet being related to a shallow water table is that a fluctuating sea level history will result in a sympathetic fluctuation in the water table and hence a history of calcrete development that will reflect the sea level history. Similarly, the unique occurrence of tree-induced precipitation of calcrete will result in lenses of calcrete breccia floatstone in soils where such trees are up-rooted by storms, a stratigraphic and lithologic feature distinct to this region.

Currently 580 ha of the Leschenault Peninsula is in the Conservation Estate as a nature reserve (Leschenault Peninsula Conservation Park) vested in the National Parks and Nature Conservation Authority (Department of Conservation and Land Management 1998), but this is based more on its biological values than its geological attributes. We argue that geological attributes should be added as criteria in identifying terrain for the Conservation Estate in general, criteria that are not currently pursued in Western Australia, and that the Leschenault Peninsula and its leeward estuarine lagoon should be viewed as a geopark with a focus on its important geological features and that these concepts be added to the notion of its existence as conservation park.

REFERENCES

Alderman, A.R. and Skinner, C.W. (1957). Dolomite sedimentation in the south-east of South Australia. *American Journal of Science* **255**, 561-567.

Belperio, A.P. (1995). Quaternary. In 'The geology of South Australia. Volume 2. The Phanerozoic' (Eds J.F. Dexel and W.V. Preiss) pp. 219-280.

Brocx M. (2008). 'Geoheritage: from global perspectives to local principles for conservation and planning'. (Western Australian Museum: Western Australia).

Brocx M. and Semeniuk V. (2007). Geoheritage and geoconservation – history, definition, scope and scale. *Journal of the Royal Society of Western Australia* **90**, 53-87.

Brocx M. and Semeniuk V. (2010). Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying geodiversity and sites of significance in Western Australia. *Journal of the Royal Society of Western Australia* **93**, 81-113.

Bureau of Meteorology (1988). 'Climatic Atlas of Australia'. (Department of Administrative Services, Commonwealth of Australia: Canberra).

Cresswell, I.D. (2000). Ecological significance of freshwater seeps along the western shore of the Leschenault Inlet estuary. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 85-292.

Department of Conservation and Land Management (1998). Leschenault Peninsula Management Plan 1998-2008. Management Plan 38. (Department of Conservation and Land Management *for* The National Parks and Nature Conservation Authority: Western Australia).

Doyle, P., Easterbrook, G., Reid, E., Skipsey, E. and Wilson, C. (1994). Earth Heritage Conservation. In 'United Kingdom' (Ed C Wilson). (City Print [Milton Keynes] Ltd.).

Gallois, R.W. (1965). 'The Wealdon District: British Regional Geology'. (Natural Environment Research Council Institute of Geological Sciences).

Geddes, M. and Butler, A.J. (1984). Physicochemical and biological studies on the Coorong Lagoons, South Australia, and the effect of salinity of the distribution of the macrobenthos. *Transactions of the Royal Society of South Australia* **108**, 51–62.

Geological Survey of Western Australia (1990). 'Geology and mineral resources of Western Australia'. (Geological Survey of Western Australia Memoir 3).

Harvey, N. (2006). Holocene coastal evolution: barriers, beach ridges, and tidal flats of South Australia. *Journal of Coastal Research* **22**, 90-99.

Holmes, A. (1966). 'Principles of Physical Geology'. (Thomas Nelson, London).

Logan, B.W. (1970). Sedimentary environments of Shark Bay Western Australia. In 'Carbonate Sedimentation and Environments, Shark Bay, Western Australia'

(Eds B.W. Logan, G.R. Davies, J.F. Read and D.E. Cebulski) pp. 1-37. (American Association of Petroleum Geologists Memoir 13: Tulsa, Oklahoma).

Logan, B.W. (Ed) (1974). 'Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia'. (American Association of Petroleum Geologists Memoir 22. Tulsa, Oklahoma).

Melville, R.V. and Freshney, E.C. (1982). 'The Hampshire Basin and Adjoining Areas: British Regional Geology'. (Natural Environment Research Council Institute of Geological Sciences).

Murray-Wallace, C.V., Belperio, A.P., Bourman, R.P., Cann, J.H., and Pricea, D.M. (1999). Facies architecture of a last interglacial barrier: a model for Quaternary barrier development from the Coorong to Mount Gambier Coastal Plain, southeastern Australia. *Marine Geology* **158**, 177–195.

Pen, L., Semeniuk, V. and Semeniuk, C.A. (2000). Peripheral wetland habitats and vegetation of Leschenault Inlet estuary. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 293-316.

ProGEO (2002). 'Natural and Cultural Landscapes: the Geological Foundation Paper' read at ProGEO Dublin 9-11/9/2002 at Dublin Castle, Dublin, Ireland.

Revets, S.A. (2000). Foraminifera of Leschenault Inlet. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 365-375.

Roy, P.S. (1984). New South Wales estuaries: their origin and evolution. In 'Coastal geomorphology in Australia' (Ed B.G. Thom) pp. 99-121. (Academic Press, Sydney).

Roy, P.S. and Crawford, E.A. (1979). Holocene geological evolution of southern Botany Bay – Kurnell region, central New South Wales. *N.S.W. Geological Survey Records* **20**, 159-250.

Roy, P.S., Cowell, P.J., Ferland, M.A. and Thom, B.G. (1994). Wave-dominated coasts. In 'Coastal evolution – late Quaternary shoreline morphodynamics' (Eds R.W.G. Carter and C.D. Woodroffe) pp. 121-186. (Cambridge University Press, Cambridge).

Searle D J and Semeniuk, V. (1985). The natural sectors of the Rottnest Shelf Coast adjoining the Swan Coastal Plain. *Journal of the Royal Society of Western Australia* **67**, 116-136.

Semeniuk, V. (1983). The Quaternary stratigraphy and geological history of the Australind-Leschenault Inlet area, Western Australia. *Journal of the Royal Society of Western Australia* **66**, 71-83.

Semeniuk, V. (1985). The age structure of a Holocene barrier dune system and its implication for sealevel history reconstructions in southwestern Australia. *Marine Geology* **67**, 197-212.

Semeniuk, V. (1986a). Holocene climate history of coastal SW Australia using calcrete as an indicator. *Palaeogeography Palaeoclimatology Palaeoecology* **53**, 289-308.

Semeniuk, V. (1986b). Calcrete breccia floatstone in Holocene sand developed by storm-uprooted trees. *Sedimentary Geology* **48**, 183-192.

Semeniuk, V. (1996). An early Holocene record of rising sealevel along a bathymetrically complex coast in southwestern Australia. *Marine Geology* **131**, 177-193.

Semeniuk, V. (1997). Pleistocene coastal palaeogeography in southwestern Australia - carbonate and quartz sand sedimentation in cuspate forelands, barriers and ribbon shoreline deposits. *Journal of Coastal Research*, **13**, 468-489.

Semeniuk, V. (1998). 'Identifying sites of geoheritage in the region of the RFA (Regional Forest Agreement), Southwestern Australia - a Discussion'. Report to Department of Conservation and Land Management, Manjimup, and to Australian Nature Conservation Agency (now Environment Australia), Canberra, ACT.

Semeniuk, V. (2000). Sedimentology and Holocene stratigraphy of Leschenault Inlet. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 255-274.

Semeniuk, V. (2010). A note on calcite precipitates as encrustations around sea rush roots and rhizomes and as laminae in high tidal zones of western Leschenault Inlet estuary. *Journal of the Royal Society of Western Australia* **93**, 195-199.

Semeniuk, V. and Meagher T.D. (1981a). The geomorphology and surface processes of the Australind - Leschenault Inlet coastal area. *Journal of the Royal Society of Western Australia* **64**, 33-51.

Semeniuk, V. and Meagher T.D. (1981b). Calcrete in Quaternary coastal dunes in South Western Australia: a capillary-rise phenomenon associated with plants. *Journal of Sedimentary Petrology* **51**, 47-68.

Semeniuk, V., Milne, L.A. and Waterhouse, H. (2000c). The contemporary and subrecent pollen record in Leschenault Inlet: towards a palynological baseline. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 335-348.

Semeniuk, V. and Searle, D.J. (1985). Distribution of calcrete in Holocene coastal sands in relationship to climate, southwestern Australia. *Journal of Sedimentary Petrology* **55**, 86-95.

Semeniuk, V. and Searle, D.J. (1986). Variability of Holocene sealevel history along the southwestern coast of Australia - evidence for the effect of significant local tectonism. *Marine Geology* **72**, 47-58.

Semeniuk, V. and Searle, D.J. (1987). Beachridges/bands along a high energy coast in southwestern Australia - their significance and use in coastal history. *Journal of Coastal Research* **3**, 331-342.

Semeniuk, V., Semeniuk, C.A., Tauss, C., Unno, J. and Brocx, M. (2010). Walpole and Nornalup Inlets: landforms, stratigraphy, evolution, hydrology, water quality, and biota. Western Australian Museum (Monograph).

Semeniuk, V., Semeniuk, T.A. and Unno, J. (2000a). The Leschenault Inlet estuary - an overview. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 207-228.

Semeniuk, V., Tauss, C. and Unno, J. (2000b). The white mangrove *Avicennia marina* in the Leschenault Inlet area. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**, 317-334.

Semeniuk, V., Semeniuk, C. A., Tauss, C., Unno, J. and Brocx, M. (2010) (in press). Walpole and Nornalup Inlets: landforms, stratigraphy, evolution, hydrology, water quality, and biota. Western Australian Museum (Monograph).

Shelton, J.S. (1966). 'Geology Illustrated'. (Freeman and Company, USA).

von der Borch, C.C. and Lock, D. (1979). Geological significance of Coorong dolomites. *Sedimentology* **26**, 813-824.

Warren, J.K. (1983). Pedogenic calcrete as it occurs in Quaternary calcareous dunes in coastal South Australia. *Journal of Sedimentary Petrology* **53**, 787-796.

Whittaker, R. H. (1972). Evolution and measurement of species diversity. *Taxon* **21**, 213-251.

Wimbledon, W.A., Benton, M.J., Black, R.E., Bridgeland, D.R., Cleal, C.J., Cooper, R.G. and May, V.J. (1995). The development of a methodology for the selection of British geological sites for conservation: Part 1. *Modern Geology* **20**,159.

Wimbledon, W.A.P. (1996). 'GEOSITES: A new IUGS initiative to compile a global comparative site inventory as an aid to international and national conservation activity'. (ProGEO 1996-4, 1-5).

Wurm, P.A.S. and Semeniuk, V. (2000). The Leschenault Inlet estuary: physical features and habitats for benthic fauna. *Journal of the Royal Society of Western Australia* Special Issue on the Leschenault Inlet Estuary **83**,